Impact of Probabilistic Weather Forecasts
on Flight Routing Decisions

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Flight delays in the United States have been steadily increasing, along with the increase in air traffic. During the four-month period from May through August of 2005, weather related delays for air traffic accounted for roughly 70% of all reported delays. The current state of forecasting weather in strategic (2-6 hours) time frame is not dependable for long-term planning. There is a general consensus that to manage traffic volume of the next few decades, probabilistic weather forecasting will be necessary. This paper proposes an approach of describing probabilistic weather prediction for Traffic Flow Management use, and a general method using this prediction for estimating flight lengths and delays in the National Airspace System. A specific Traffic Flow Management environment is utilized for the study, where these concepts are integrated. A Probability Intrusion Parameter is devised to help meteorologists create a description of weather that is pertinent to air traffic flow. The current convective weather forecasting is employed in developing this methodology to help decision-makers achieve efficient traffic flow and flight planning.

I.   Introduction

Flight delays in the United States have been steadily increasing year after year, along with the increase in air traffic. During the four-month period from May through August of 2005, weather related delays accounted for roughly 70% of all reported delays. The current weather prediction in tactical (within 2 hours) timeframe is at manageable levels, however, the state of forecasting weather for strategic (2-6 hours) time frame is still not dependable for long-term planning. In the absence of reliable severe weather forecasts, the decision-making for flights longer than two hours is challenging. This paper deals with an approach of using probabilistic weather prediction for Traffic Flow Management use, and a general method using this prediction for estimating expected values of flight length and delays in the National Airspace System (NAS). The current state-of-the-art convective weather description is employed to aid the decision makers in arriving at solutions for efficient traffic flow and flight planning.

The six-agency effort working on the Next Generation Air Transportation System (NGATS) have considered weather-assimilated decision-making as one of the principal foci out of a list of eight. The weather Integrated Product Team has considered integrated weather information and improved aviation weather forecasts as two of the main efforts (Ref. 1, 2). Recently, research has focused on the concept of operations for strategic traffic flow management (Ref. 3) and how weather data can be integrated for improved decision-making for efficient traffic management initiatives (Ref. 4, 5). An overview of the weather data needs and benefits of various participants in the air traffic system along with available products can be found in Ref. 6. Previous work related to use of weather data in identifying and categorizing pilot intrusions into severe weather regions (Ref. 7, 8) has demonstrated a need for better forecasting in the strategic planning time frames and moving towards a probabilistic description of weather (Ref. 9). This paper focuses on specified probability in a local region for flight intrusion/deviation decision-making. The process uses a probabilistic weather description, implements that in an air traffic assessment system to study trajectories of aircraft crossing a cut-off probability contour. This value would be useful for meteorologists in creating optimum distribution profiles for severe weather. Once available, the expected values of flight path and

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aggregate delays are calculated for efficient operations. The current research, however, does not deal with the issue of multiple cell encounters, as well as echo tops, and will be a topic of future work.

The paper first describes an environment available for studying the integrated air traffic and weather products in Section II. A different approach to prescribing probabilistic weather and integrating the flight parameters is described in Section III. Section IV deals with using this approach for flight path decision-making, along with some preliminary results. Summary and conclusions based on current work are presented at the end.

II.   Integration of Convective Weather Formats in FACET

In order to study the impact of convective weather on air traffic, a tool with the integrated information is needed. The Future ATM (Air Traffic Management) Concepts Evaluation Tool (FACET) provides this capability. FACET (Ref. 10) is a simulation and modeling environment developed at the NASA Ames Research Center for exploration and development of ATM concepts. It deals with traffic in the NAS, and the capability of studying Air Route Traffic Control Center (ARTCC) or sub-level of Sectors is available. FACET can be run in playback, simulation, hybrid or real-time modes. The playback mode provides the user a capability to understand how the NAS behaved on a prerecorded day. The simulation mode, however, allows the user to take initial conditions from a certain time and evolve the air traffic system based on available intent, in the form of flight plans and take-off times. The hybrid mode allows the user to modify a set of flights based on certain constraints, keeping the others as they flew. The real-time mode lets a user connect to a live feed of air traffic/weather data for real-time visualization and prediction
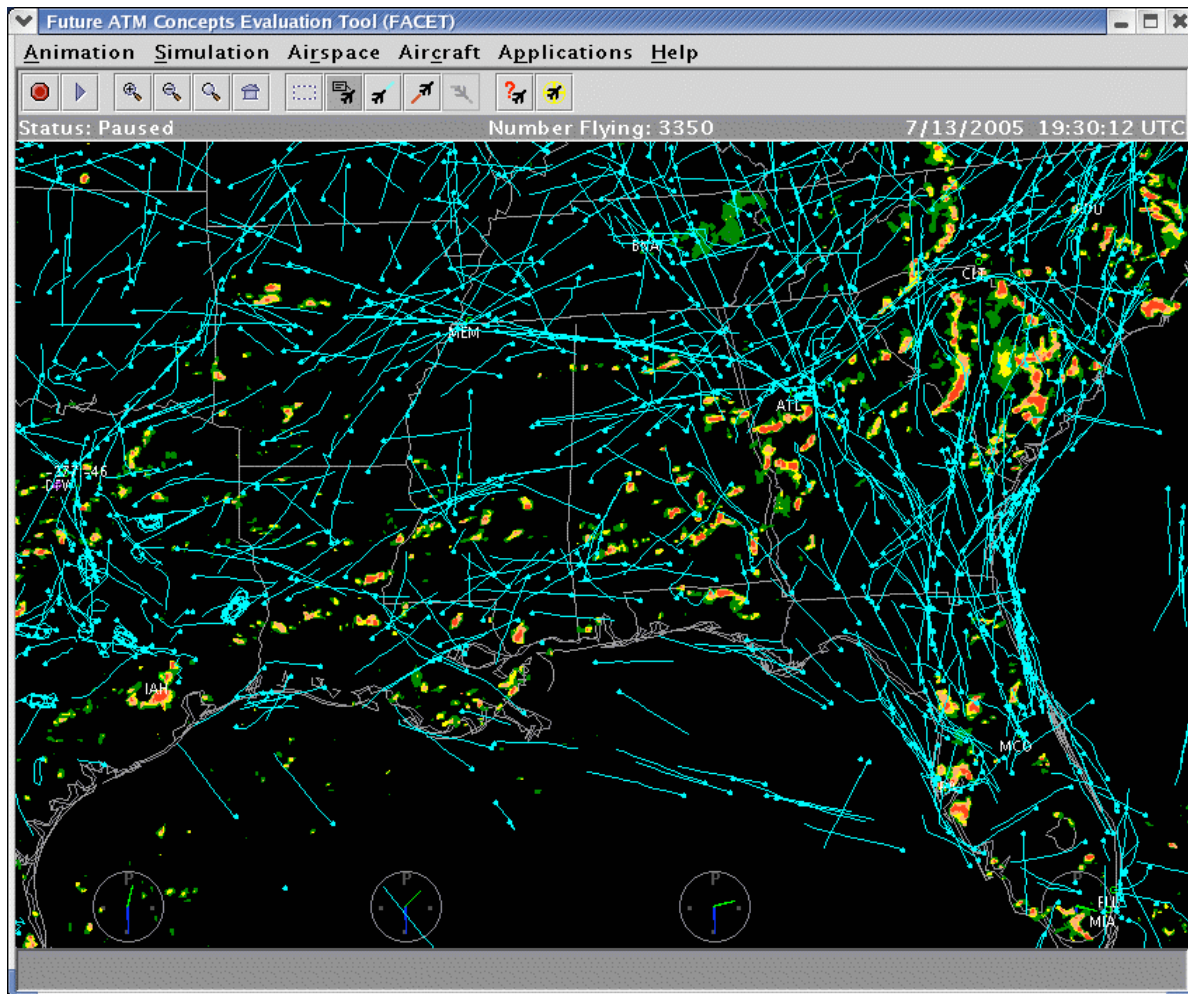

Figure 1: Integrated air traffic and Nexrad data on July 13, 2005 shown in FACET.

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purposes. FACET has the performance tables for various aircraft types along with NAS adaptations, which are used in integrating equations of motion (during a simulation) for different flights while incorporating winds aloft data. FACET is capable of reading the Enhanced Traffic Management System (ETMS) provided air traffic data and various state-of-the-art convective weather forecast products (e.g. NCWF, CCFP, Nexrad, etc.) available in the industry. The integrated information can be used for visualizing the effects of weather in real-time, as well as for planning purposes. A snapshot of traffic and weather data at 19:30 UTC on July 13, 2005 is shown in Figure 1. The southeast region of the US is shown with some of the major airports (e.g. Atlanta, GA (ATL), Orlando, FL (MCO), etc.) highlighted. The *Nex*t Generation *Rad*ar (NEXRAD) data NWS level 3 through 6 is shown in green, yellow, orange, and red. The aircraft are shown as cyan dots, with their track histories for ten minutes.

III.   Description of Probabilistic Weather

In this section, an approach for describing probabilistic weather for Traffic Flow Management is considered. For this research, the Nexrad data was used as the basis for developing the probabilistic weather description concept. This concept is described in the following sub-sections.

A. A Model of Probability

The National Weather Service provides Nexrad data with levels 1 through 6 based on the radar reflectivity. The level 3 or higher reflectivity roughly represents a number of 40 dBZ or higher. The digital data represent these levels on a grid. The approach used in this research assumes that this weather data will be provided as probabilities of level 3 or higher (corresponding to 40 dBZ or higher). It should be noted that in such a description, the probabilities of individual levels are not specified. So, for example, let's assume that the weather is specified as polygons shown in Figure 2 (left), where the outermost polygon represents weather of level 4, the middle polygon represents intense weather of level 5, and the innermost polygon represents extreme weather of level 6. In this paper, it's assumed that the corresponding probabilities for those polygons are 10%, 30%, and 60%, outermost to innermost, respectively. In reality, and in the future, those numbers will be provided based on the forecast computations. In conversations with meteorologists and other literature (Ref. 11), it was derived that imposing a Normal distribution, at the edges of the 10% probability contour, with the value tending to 0% at 3σ, is a reasonable assumption. This distribution is imposed at the boundary of the 30% and 60% curves as well. Then, the curves are superimposed to obtain a maximum probability curve for a particular spatial location. Figure 2 (right) represents these probabilities represented by fading colors of yellow (60%), dirty green (30%), and magenta (10%). It is believed that the National Convective Weather Forecast (NCWF-6) product from the National Center for Atmospheric Research (NCAR) will be publishing a product of this type starting mid-summer 2006. The probability curve encountered by an aircraft's flight plan is discussed next.
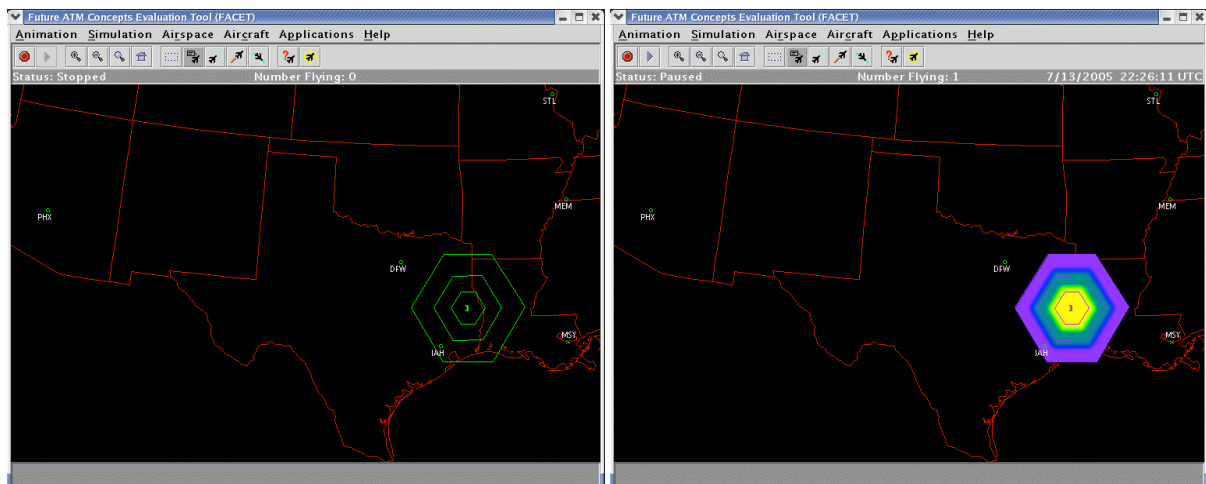

Figure 2: A deterministic (left) and probabilistic (right) representation of weather in FACET.

B. Integration of Probabilistic Weather and Flight Plans

Once the weather polygons are described as probabilities, one can use an environment like FACET (described earlier) to evaluate the weather intrusion effects on flights. In Figure 3 (left), a flight plan is shown for a flight

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FLT123 going from Phoenix, AZ to New Orleans, LA, passing through the three polygons described in Figure 2. The actual airline identifier has been changed to retain anonymity. Figure 3 (left) shows a simulated flight based on a nominal flight plan (during clear weather conditions) between the city pair, while Figure 3 (right) shows the actual tracks as flown on July 13, 2005 penetrating the outer regions of these weather contours. It should be noted that actual severe weather on that day was in the close proximity of the drawn polygons. Considering the probabilities of occurrence of severe weather, final probability curve is computed for that flight and shown in Figure 4. As can be seen from Figure 3 (left), the flight penetrates the yellow region (with a 60% probability), while the actual flight only traverses the dirty green region (with a 30% probability). These values are reflected in the graphs in Figure 4.
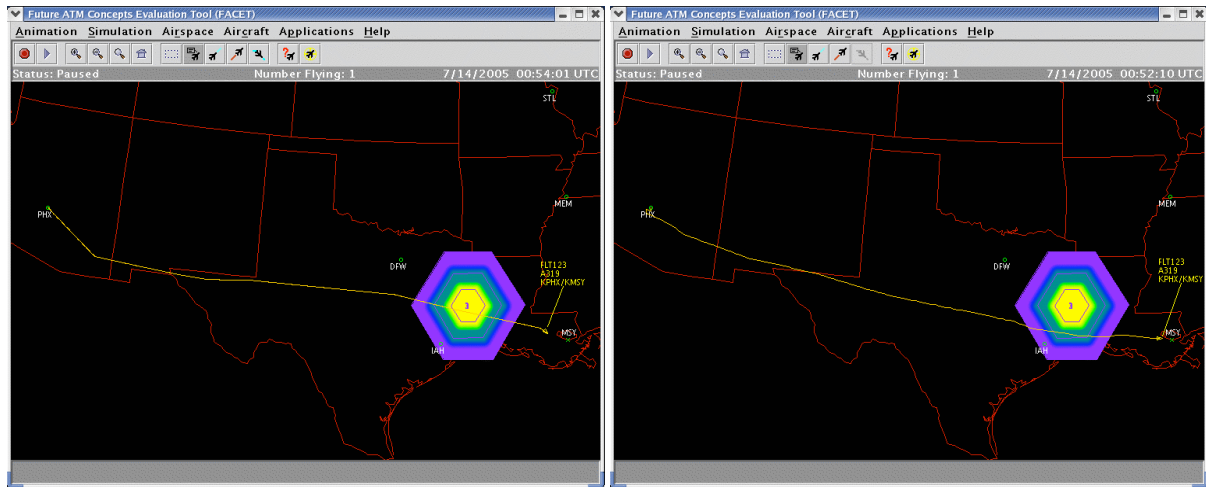

Figure 3: A Simulated flight and Actual flight history penetrating weather probability contours.
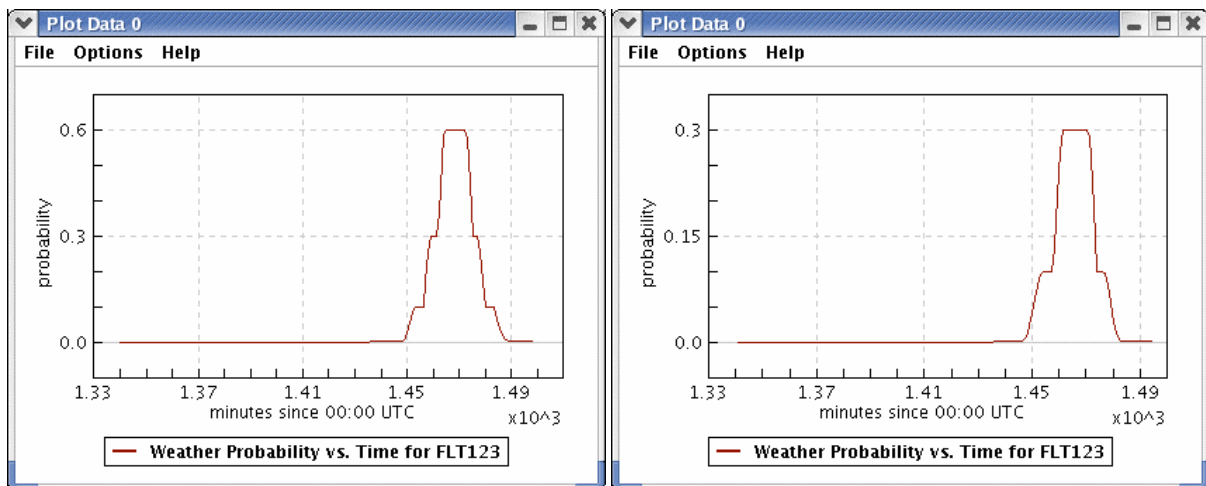

Figure 4: The traversed probabilities for the flight corresponding to the contours in Figure 3.

IV.   Traffic Flow Management (TFM) Decision-Making

With the description of various options of flight plans available to a decision maker (e.g. Airline Operations Center Flight Dispatcher), a Decision Support Tool (DST) derived from FACET can compute the effect of varying probabilities encountered by each flight plan. The question that a dispatcher often deals with is if his or her flight is going to be moved due to weather or congestion. In this research, an expected value approach is used to ascertain the flight length given the forecast of weather probabilities. On the other hand, an Air Route Traffic Control Center (ARTCC) Traffic Manager's perspective is to estimate the delays associated with a certain forecasted probabilistic

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description of weather. Based on this estimate, certain decisions would be made in terms of the type of Traffic Management Initiatives imposed. These aspects of TFM decision-making process are considered in this section.

A. Expected Value of Flight Paths Effect of Look-Ahead Time

Using the probabilities specified by a forecast product, say P_i, and computed path lengths for individual flight plan options, say L_i, one can compute the expected value, $E(L)$, as follows (Ref. 12):

$$E(L) = \sum_{i=1}^{N} L_i * P(L = L_i) \tag{1}$$

For the case of the flight FLT123 mentioned above, a simulated path length was obtained from FACET for three different cases. An automated rerouting algorithm developed during earlier research (Ref. 13) has been implemented in FACET to study automated rerouting of aircraft around weather cells or congested airspace regions. This algorithm was used to reroute flight FLT123 around the three weather polygons displayed in Figure 3 (left). Table 1 shows the FACET computed lengths and times for FLT123 to go around the various polygons. The 10%, 30% and 60% polygon rerouted lengths can be used in Equation 1 to compute E(L). This number for FLT123 is 1173.7 nm.

FCA	Length (nm)	Time (hrs)
60%	1163.8	02:41
30%	1181.9	02:44
10%	1208.4	02:47
Playback	1171.3	02:35

Table 1: Length and Time of flight to reroute around the severe weather polygons.

Table 1 also represents the total time taken by FLT123 to avoid the three polygons. In order for the rerouting algorithm mentioned above (Ref. 13) to work successfully, the user specifies how much time (look-ahead time, LAT) before the aircraft arrives at the bad weather region, that the maneuver should be started. For the numbers in Table 1, an LAT of 60 minutes was used. The three flight-time numbers can be used to effectively compute the expected time of flight as well. This number for FLT123 is 2:43. One should observe that for this flight, the actual time was 2:35, which is the last entry in Table 1. There could be many reasons for a discrepancy here, including the changes in flight plan and exact location of weather. The effect of changing LAT on the computed expected values of flight length and time will be examined and reported in the final manuscript. The computation of delays is addressed next.

B. Total Delay Estimation

Using the probabilities specified by a forecast product, say P_i, and computed delay numbers due to deviations of individual flight plan options, say D_i, the expected value of flight delays due to rerouting around weather, E(D), can be computed as follows: The expected value of the delays can be calculated, as in equation 1 as

$$E(D) = \sum_{i=1}^{N} D_i * P(D = D_i) \tag{2}$$

The final paper will have these numbers computed for the case of a simulation where flights are rerouted around certain specified probability weather contours. It will also have delays associated with one of the events around which flights deviated on July 13, 2005.

C. Probability Intrusion Parameter (PIP)

One of the parameters of prime importance to meteorologists is the Probability Intrusion (or Cut-off) Parameter (PIP). Using the approach described in Section IIIB, one can produce encountered probability profiles for all aircraft during a certain period of time, as in Figure 4. FACET was used to play back tracks of aircraft around the severe weather contours. While playing the data, if an aircraft traveled through or around any of the severe weather contours, then the value of probability at that point was noted. A time history of this probability traversal or

intrusion parameter can be plotted. A sample of such flight-encountered probabilities for 4 different aircraft is shown in Figure 5 (left). Computing a histogram of maximum probability encountered or traversed by all intruding aircraft during this time period is shown in Figure 5 (right). Based on the histogram, one can see that most of the aircraft, during this period of time, avoid the 30% probability contour. There are a few flights, which traverse through the 40-60% contours or essentially going through the severe weather region. There are several reasons why this may happen. The aircraft may be landing at an airport very close to the boundary of the polygon (e.g. IAH, Houston, TX, is very close to the boundary). Another reason may be the echo tops, which indicate how high the convection exists. If flights are going *over* the weather, they appear to be traversing through the high probability contours. In the final paper, some more analysis of PIP will be performed and additional results for a specific severe weather event will be presented. If possible, the analysis will include the variation of PIP with various parameters like the aircraft type, flight operator, etc.
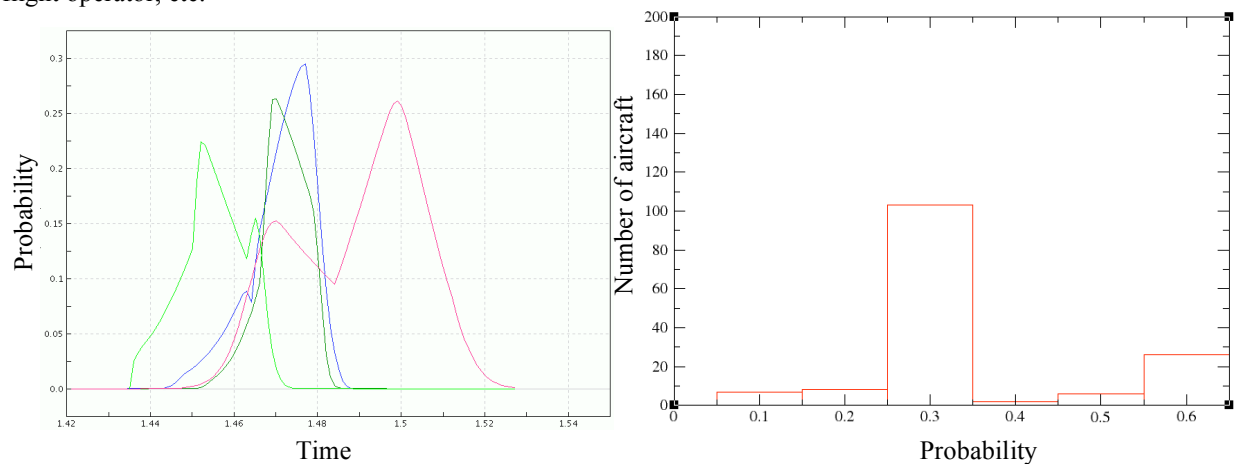

Figure 5: Encountered probabilities of some aircraft (left) and corresponding frequency histogram (right).

V. Summary and Conclusions

A different approach is presented for probabilistic weather description, wherein probabilities of encountering level 3 or higher are used for TFM decision-making. This description was used to arrive at an expected value for flight path lengths and total rerouting deviation delays. These calculations can be performed by the DST of choice of the flight planners and operators of the airspace. An additional histogram was presented with the cut-off value of probability, which flights generally do not intrude. Such a quantitative measure would be of tremendous value to the meteorologists in creating these stochastic forecasts.

In this research, the severe weather echo tops are not considered, which may have a significant impact on the analysis and will be considered in a future study. There are additional factors, which may have an important contribution to the computation of probability of severe weather intrusion histogram. Some of these factors like look-ahead time (LAT), location of weather, type of aircraft, operator of flight (not pilot, but the Airline or General Aviation), schedule for the flight, etc., also have a significant impact on this analysis and will be addressed in a future study.

Acknowledgments

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